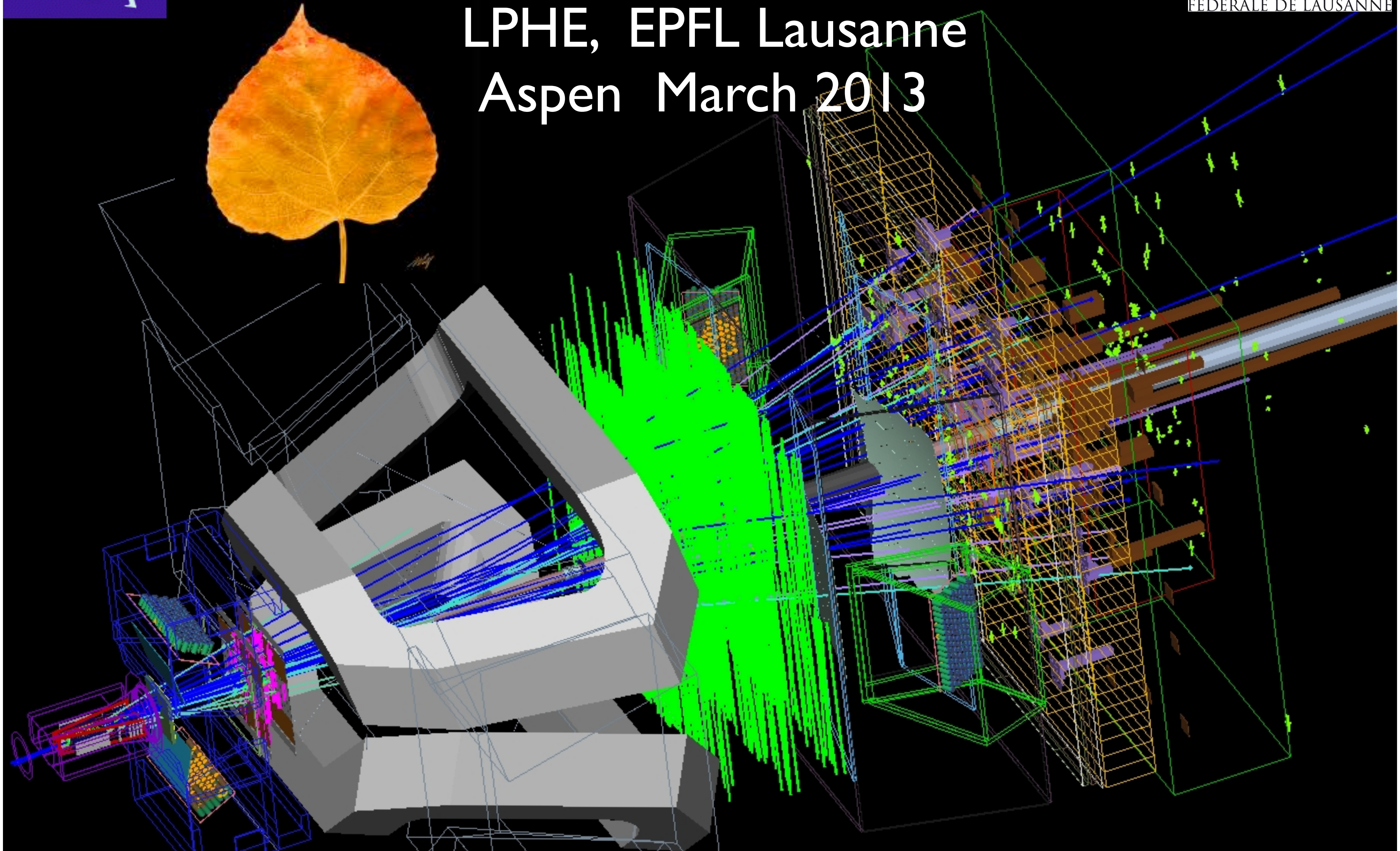
A. Bay
LPHE, EPFL Lausanne
Aspen March 2013



Toward direct searches for Higgs-like particles at LHCb

Summary

- The LHCb detector
- $H \rightarrow \tau^+ \tau^-$
- Higgs searches, b jets studies
  - b-bbar inclusive cross section
  - central-forward asymmetry in b-bbar events
- h^0 to long lived particles

The LHCb detector

Single-arm forward spectrometer:
Acceptance 10-250 mrad (V) / 10-300 mrad (H) $1.8 < \eta < 4.9$

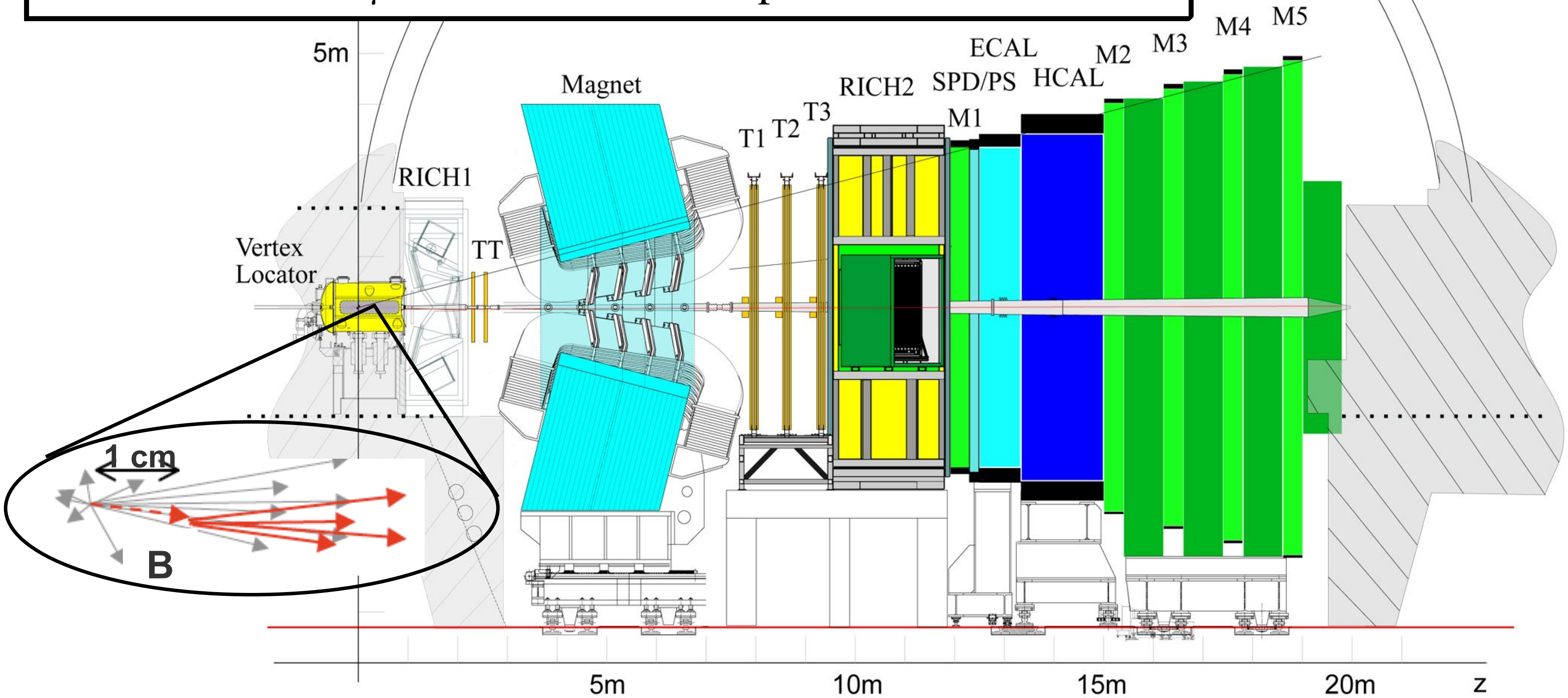
ECAL: $\sigma_E/E \sim 10\%/\sqrt{E} \oplus 1\%$ HCAL: $\sigma_E/E \sim 70\%/\sqrt{E} \oplus 10\%$
Tracking: σ_p/p 0.4% at 5 GeV/c, 0.6% at 100 GeV/c

Particle ID from two RICHes, muon chambers
Vertex detector: 20 μm IP resolution at $p_T = 2$ GeV/c

Data collected:

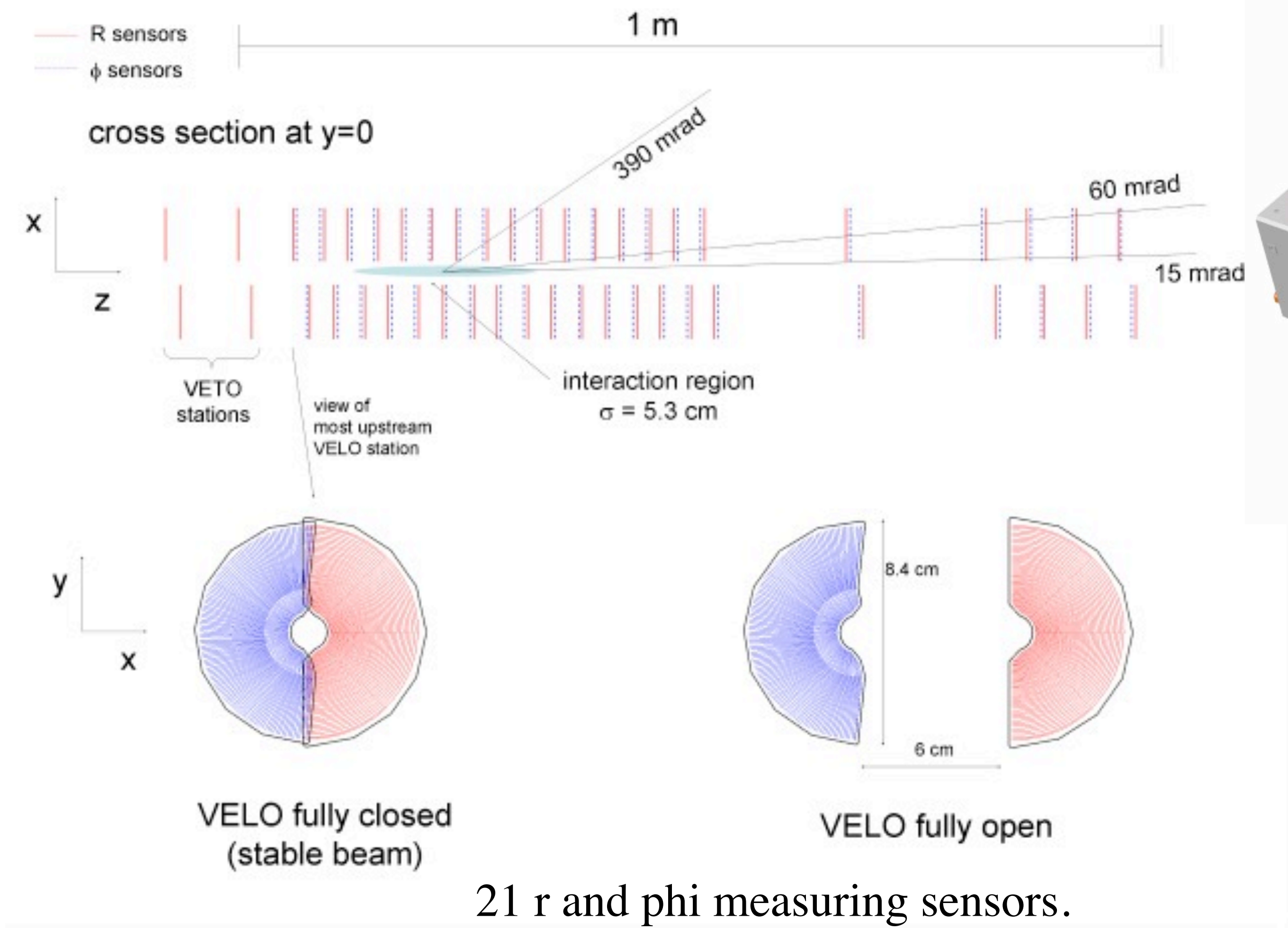
2010:	37	1/pb	7 TeV
2011:	1	1/fb	7 TeV
2012 :	2.1	1/fb	8 TeV

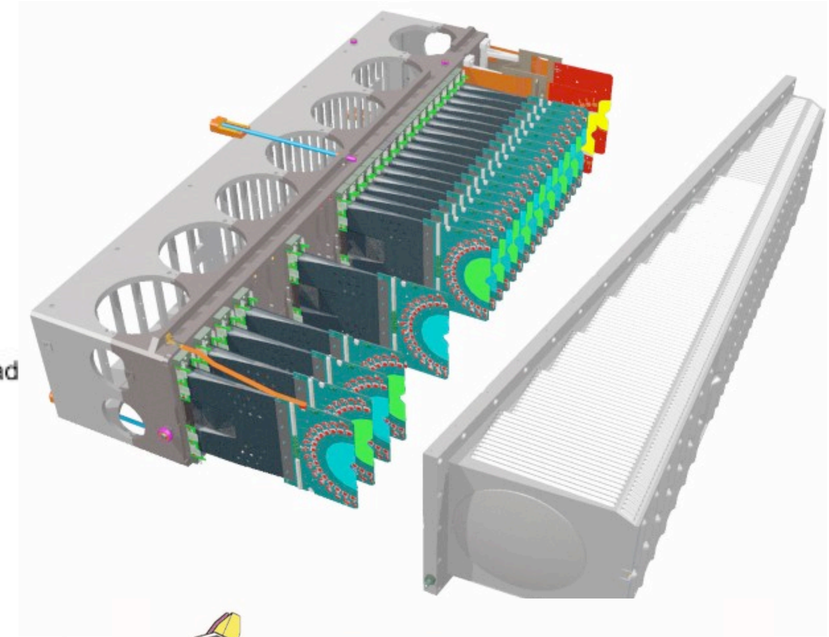
average pileup kept ~ 2

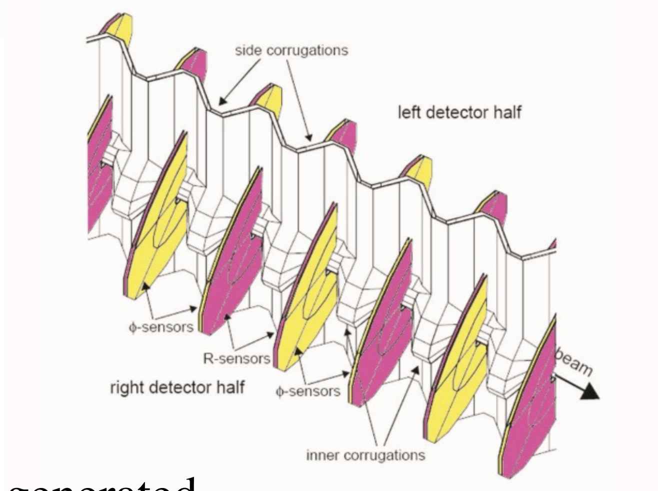


VErtex LOcator (VELO)

Material budget ~ 0.22 X^0

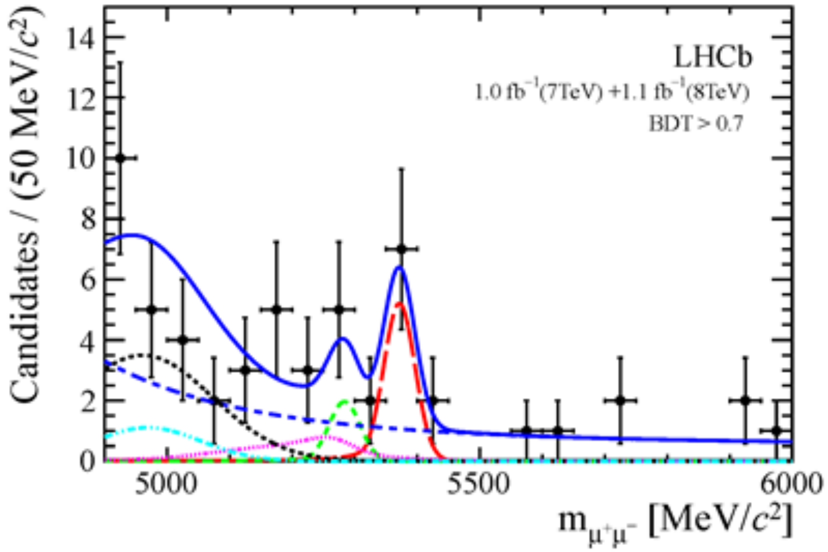






21 r and phi measuring sensors.
A thin Al screen to protect from the RF noise generated by the passing beam bunches.

LHCb playground



New Physics hunting via indirect searches

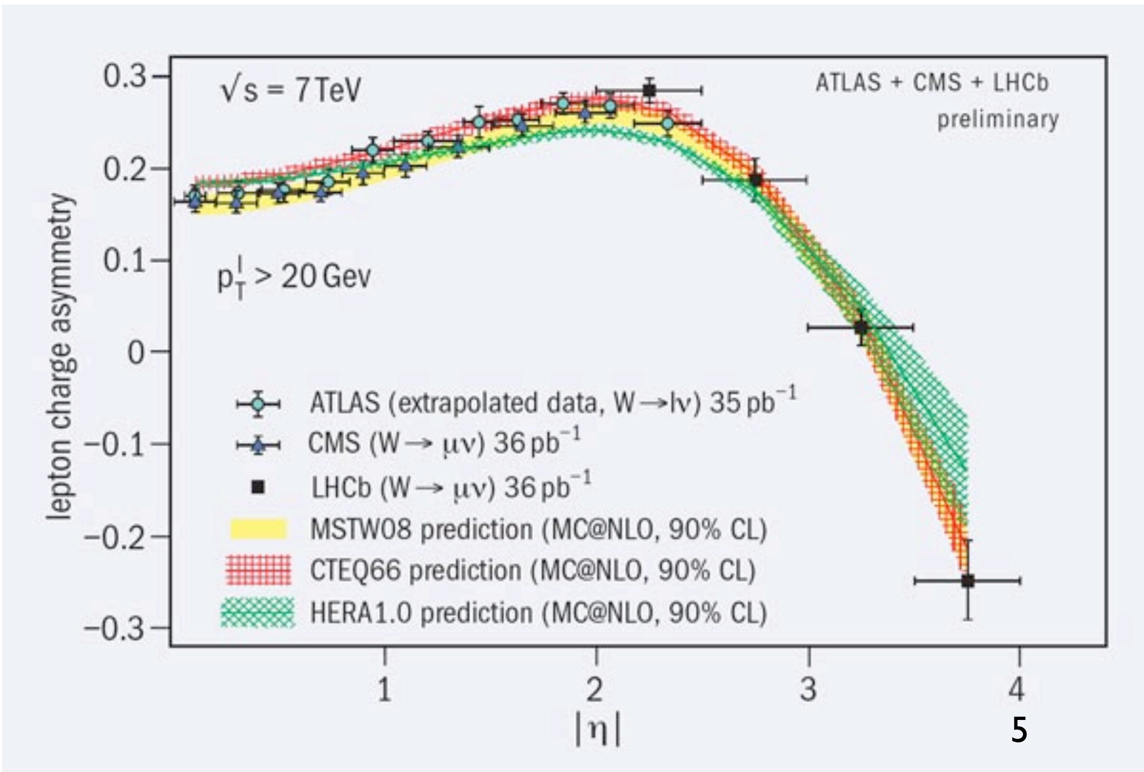
$$B_s^0 \to \mu^+\mu^-$$

Predicted BR = (3.54 ± 0.30) 10^{-9}

arXiv:1208:0934 & PRL 109 041801 (2012)

Observed BR = $3.2\,^{+1.4}_{-1.2}(\mathrm{stat})\,^{+0.5}_{-0.3}(\mathrm{syst})$

Phys. Rev. Lett. 108 (2012) 231801
LHCb-CONF-2012-043



Full story in
C. Langenbruch's talk

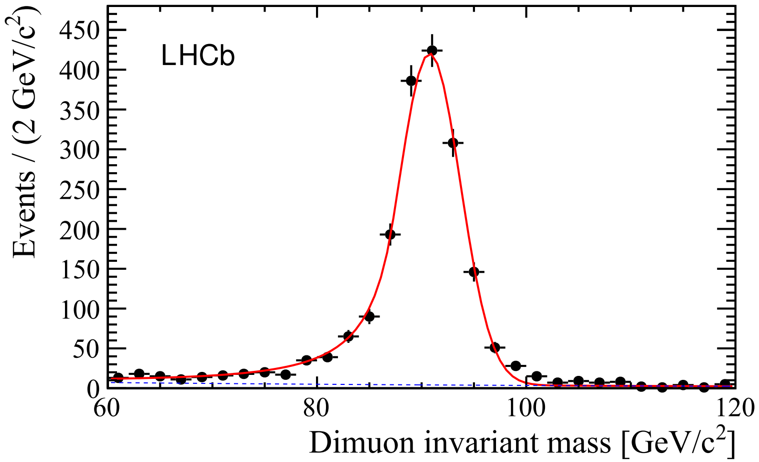
Physics measurements in kinematical regions complementary to ATLAS & CMS

$$A_W = \frac{\sigma_{W^+} - \sigma_{W^-}}{\sigma_{W^+} + \sigma_{W^-}}$$

JHEP 6 (2012) 58

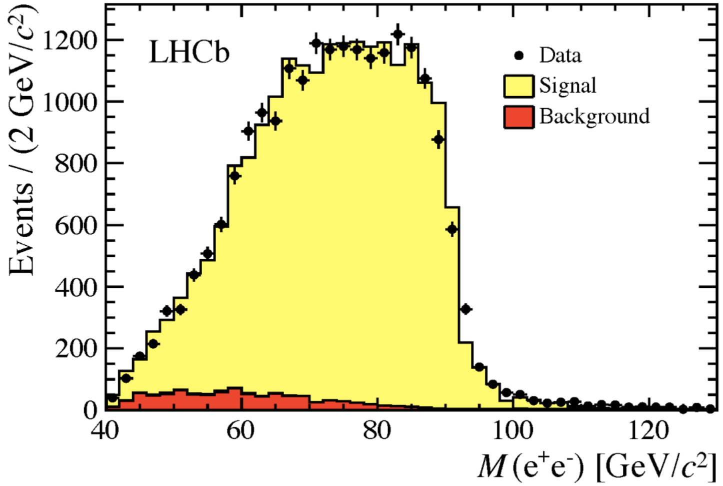
An appetiZer

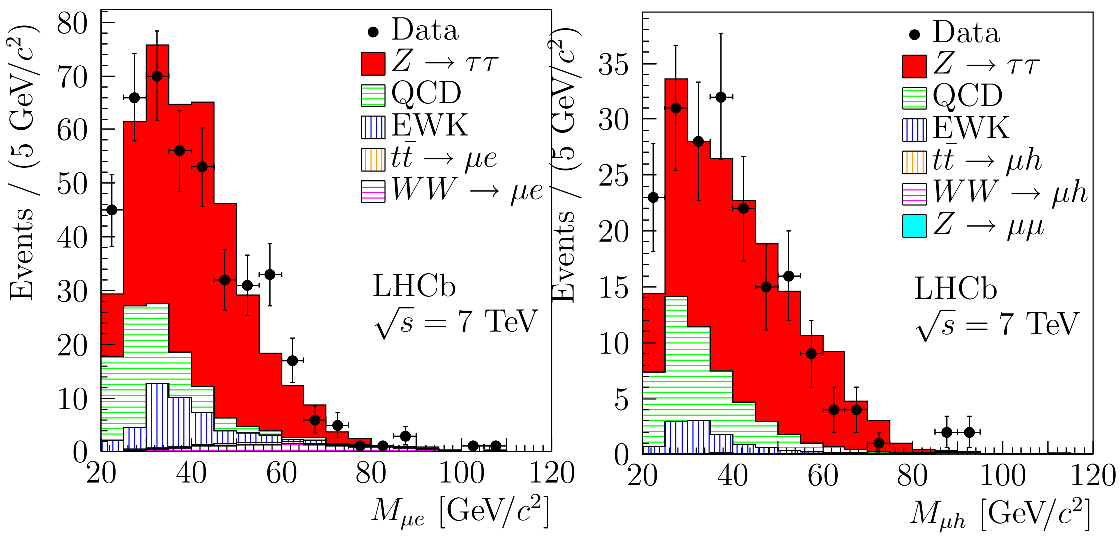
Z → μμ (37 pb^{-1})
JHEP 2012, 6 (2012), 58
1212.4620 [hep-ex]
See also Z+jet: **LHCb-CONF-2012-016**



Z → ee (0.95 fb^{-1})
- saturation in the ECAL
- bremsstrahlung

LHCb-PAPER-2012-036
1212.4620v2 [hep-ex]





Z → ττ (1 fb^{-1})

LHCb-PAPER-2012-029
1210.6289 [hep-ex]

$H \rightarrow \tau^+ \tau^-$

Goal: set limits on neutral Higgs production in the **forward** region in pp collisions at 7 TeV.

DATA sample $L \sim 1\ fb^{-1}$ collected in 2011 at 7 TeV

Five analysis streams:

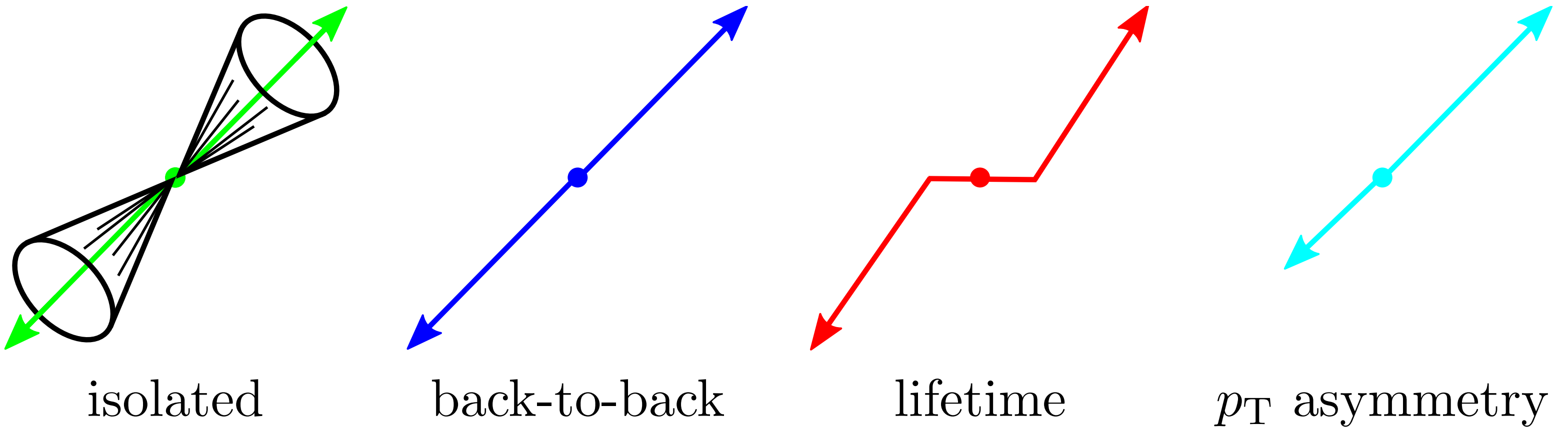
di-muon, muon+electron, electron+muon, muon+hadron, electron+hadron.

First particle $p_T > 20$ GeV/c, second $p_T > 5$ GeV/c, zero total charge.

Leptons must be isolated, and with some impact parameter wrt primary vertex.

The couple must be ~back-to-back $\Delta\phi > 2.7$ rad, mass > 20 GeV/c^2.

The momentum asymmetry is defined as the absolute difference between the transverse momenta of the two τ lepton decay product candidates over their sum, and is required be greater than 0.3 for the di-muon stream.

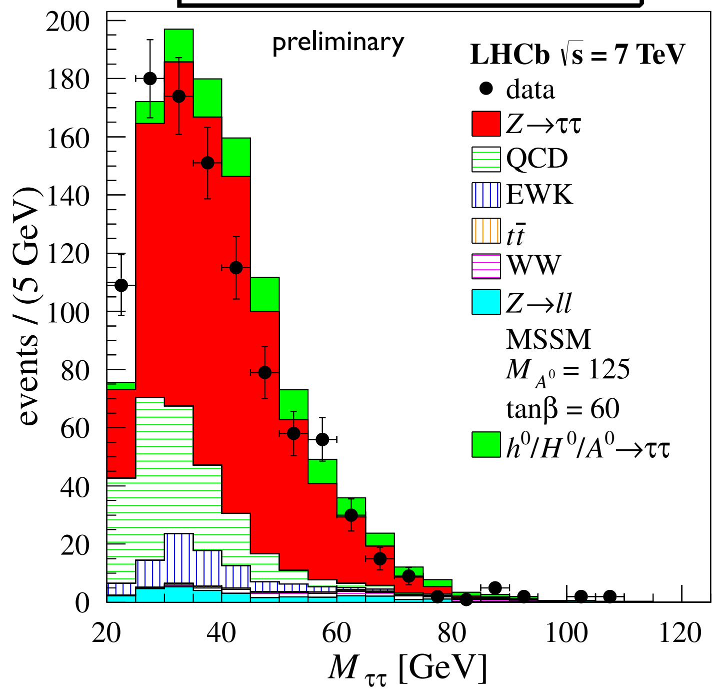


$H \to \tau^+ \tau^-$

SIGNALS

Following LHC Higgs Cross Section Working Group recommendations.
SM: Model independent. Cross sections from DFG.
MSSM: Can only be model dependent: chose $m_{h^0}^{max}$ scenario, which leaves only M_{A^0} and tan β free.
Cross sections and efficiencies functions of M_{A^0} and tan β, from gg fusion and bbbar associated production (HIGLU, GGH@NNLO, BBH@NNLO)
Contributions from h^0, A^0, and H^0 are summed.
Branching fractions with FeynHiggs 2.7.4.
Efficiencies for the signal from data (same as $\mathbf{Z \to \tau\tau}$ analysis)

All streams combined



BACKGROUNDS

$Z \to \tau^+ \tau^-$: shape from simulation, theoretical cross section, efficiency from data.

QCD: leptonic b- or c-hadron decay or misidentified hadron. Shape from isolation sideband, normalization from same-sign.

EWK: lepton from W or Z, second particle from underlying event. Shape from simulation, normalized from same-sign.

top/WW: leptonic decays. Taken from simulation.

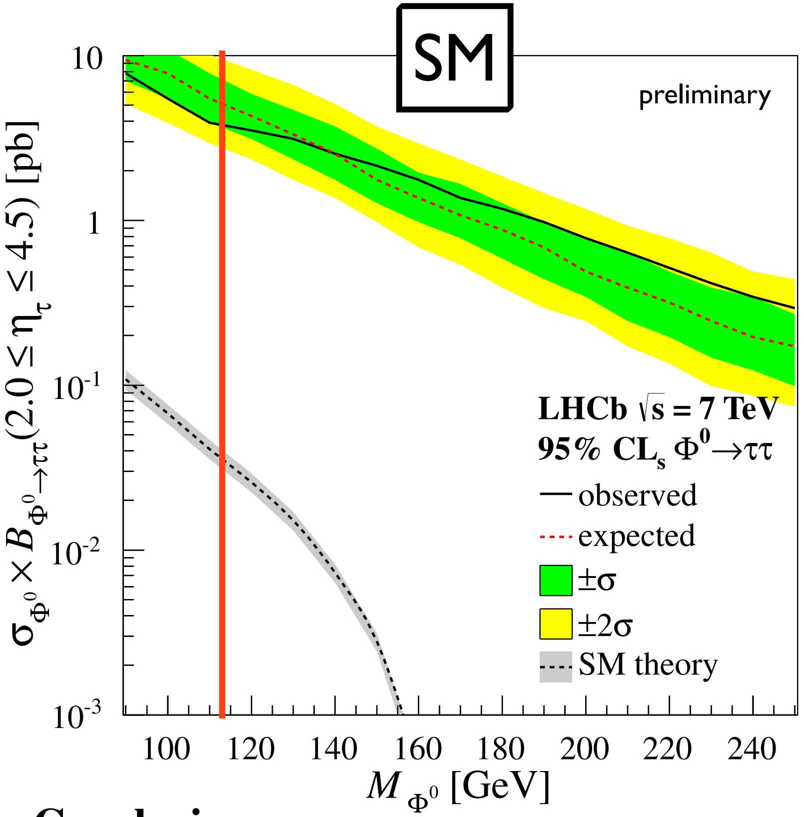
$Z \to \ell\ell$: shape from sidebands, normalization from peak or mis-id rates.

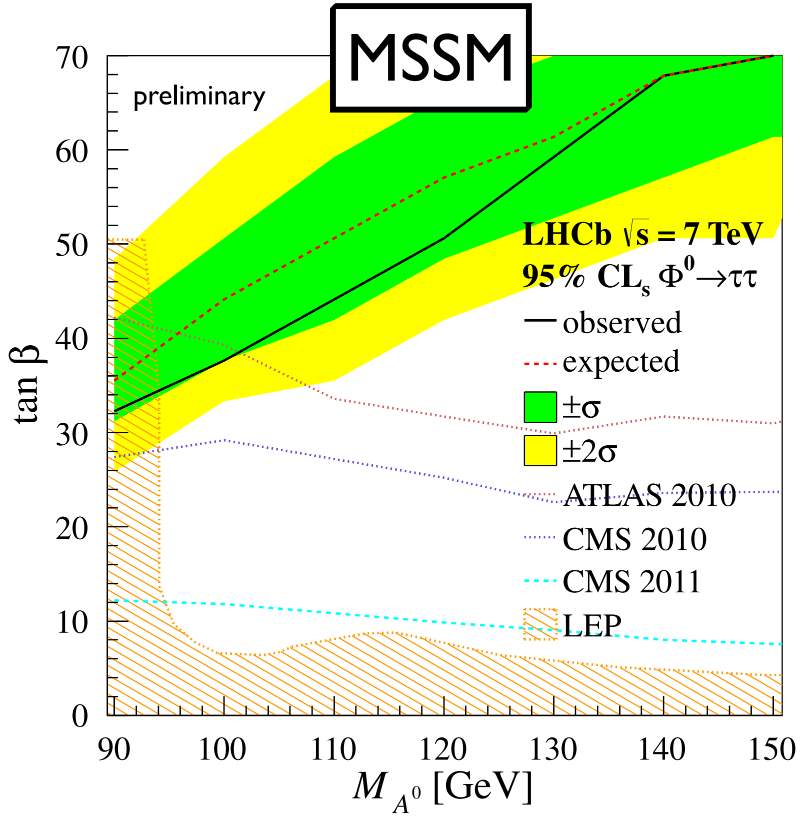
$H \rightarrow \tau^+ \tau^-$

Calculate asymptotic limit from profile ratio of extended likelihood using mass shape
(Eur. Phys. J. **C71** (2011) 1554, arXiv:1007.1727)

Upper limits calculated at CLs = 95 %

MSSM limits compared to ATLAS, CMS, and LEP results





Conclusion:

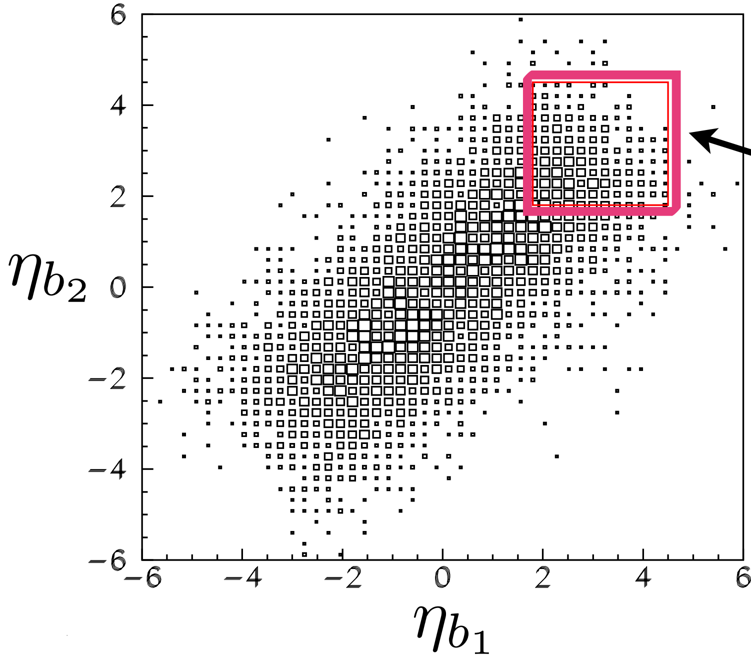
Model independent search for Higgs $\rightarrow \tau^+ \tau^-$ cross section times branching fraction upper bound at ~ 3 pb for an Higgs mass of 125 GeV/c^2, both τ in $2 < \eta < 4.5$.

In the context of the m_{h0}^{max} scenario, values above tan β from 32 to 70 are excluded for the A^0 mass range from 90 to 150 GeV /c^2.

SM(like)-Higgs studies

MC studies for the detection of Higgs bosons in associated production with Z or W can be found in CERN thesis:

C. Currat: CERN-THESIS-2001-024
L. Locatelli: CERN-THESIS-2007-073
V. Coco: CERN-THESIS-2008-101
C. Potterat: CERN-THESIS-2010-074



LHCb acceptance region

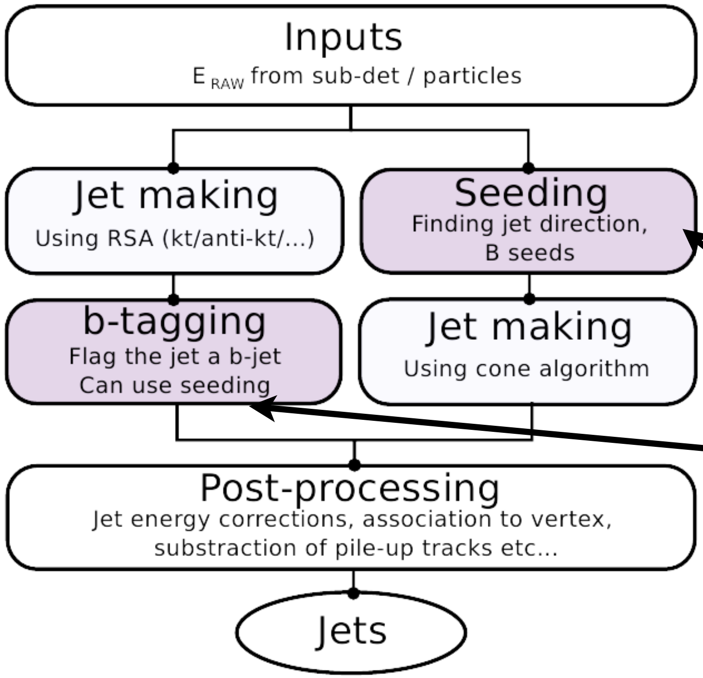
The fraction of events with BOTH b quarks from H decay in LHCb acceptance is ~ 5% at 7 TeV and 11% at 14 TeV.
Similar acceptance for the lepton from Z or W.

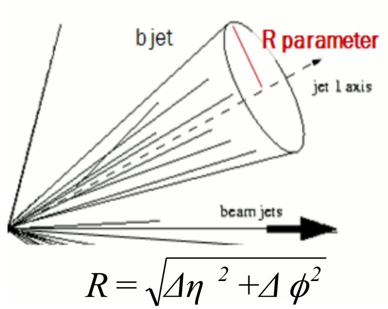
Analysis of 2011 and 2012 data ongoing.

This activity has triggered the preparation of several tools for jet reconstruction, calibration, beauty-jets tagging...

Jets with beauty

recombination sequence algorithm

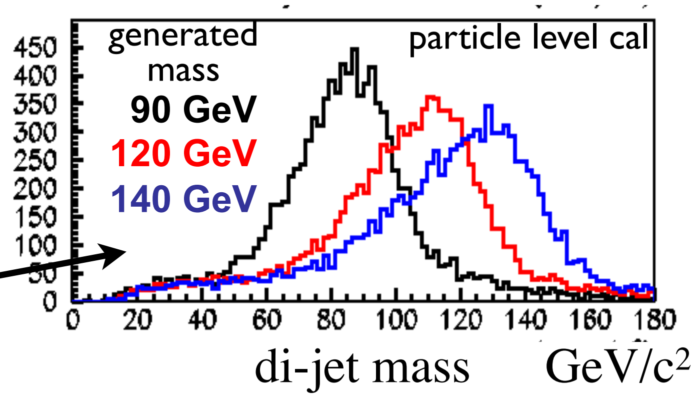




b-jet tagging exploiting the excellent spatial resolution of the vertex locator.

Jet energy must be corrected for
* portion of jet outside the acceptance
* saturation of calorimeter cells
* ...

=> ~35 % FWHM mass(b di-jet) resolution reported in CERN-THESIS-2010-074.
Not the end of the story...

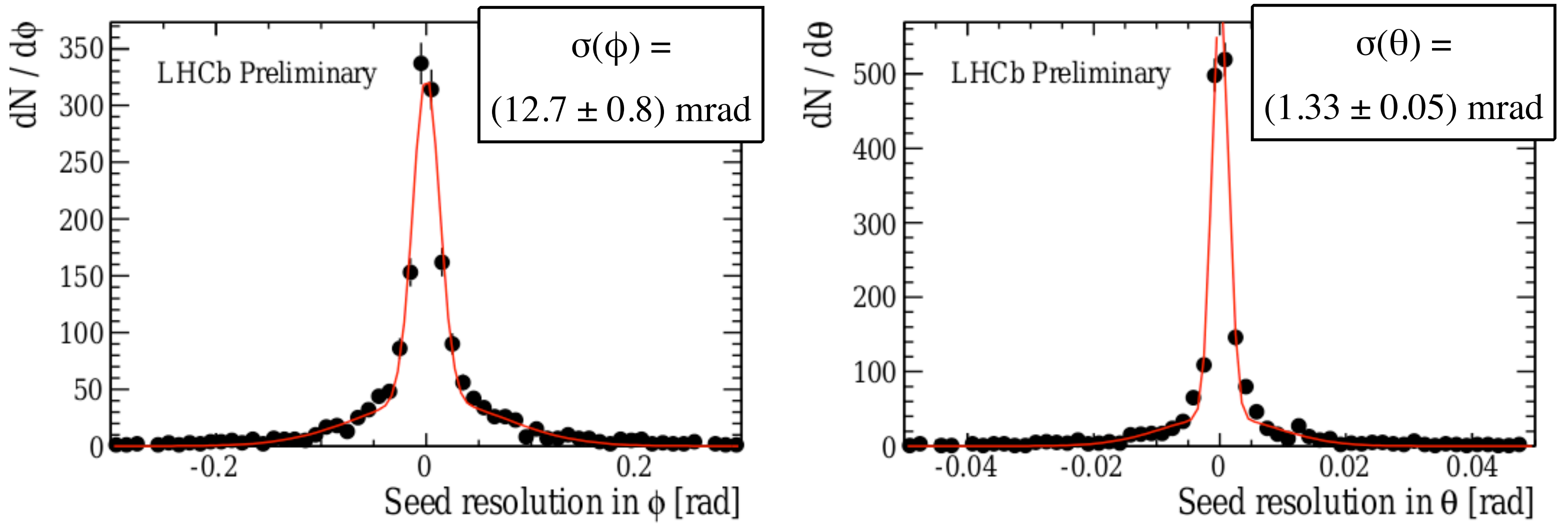


$\sigma(b\bar{b})$ inclusive

DATA sample: consider only events with ONE reconstructed primary vertex ($L = 2.6\ pb^{-1}$)

Partial b-hadron reconstruction: 3 or 2 tracks vertices give seeds with total charge $\pm1, 0$ respectively. Merge seeds when they are too close, and if final mass < $5.5\ GeV/c^2$.

=> Seeds approximate very well the initial B hadron direction



Energy correction from MC to recover the b-hadron energy.

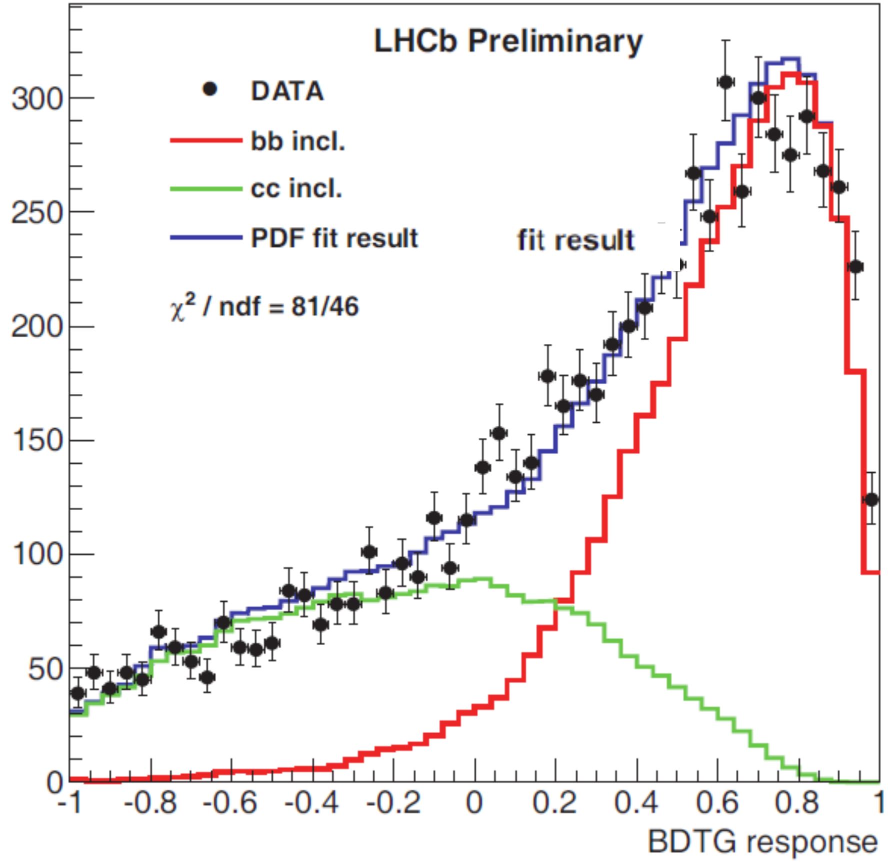
Selecting events with exactly 2 seeds within the fiducial volume: $\eta \in (2.5 - 4.0)$ and $p_T > 5\ GeV/c$

$\sigma(b\bar{b})$ inclusive

Inclusive *b* seeding efficiency
- from MC: *(81.6 ± 0.7)%*
- x-check with data: tag jet with other side $B \to D\pi$:
  (82.5 ± 3.0)%

global efficiency for b events $8\ 10^{-4}$ for c events $1.8\ 10^{-5}$

BDT to get the b-bbar and c-cbar contributions, 4 variables:
seed p_T, seed inv. mass, sum of IP significances,
and scalar sum of the tracks p_T wrt seed direction
x-check of the shape with (other side) $B \to D\pi$ and $D \to K\pi\pi$



Results for $\eta \in (2.5 - 4.0)$ and $p_T > 5$ GeV/c

σ (b-bbar) = (7.7 ± 0.12 (stat) ± 0.84 (syst)) μb

σ (c-cbar) = (104.6 ± 2.7 (stat) ± 11.4 (syst)) μb.

(For reference, extrapolated to full space with POWHEG we obtain 364 μb and 3353 μb, resp.)

Conclusion:

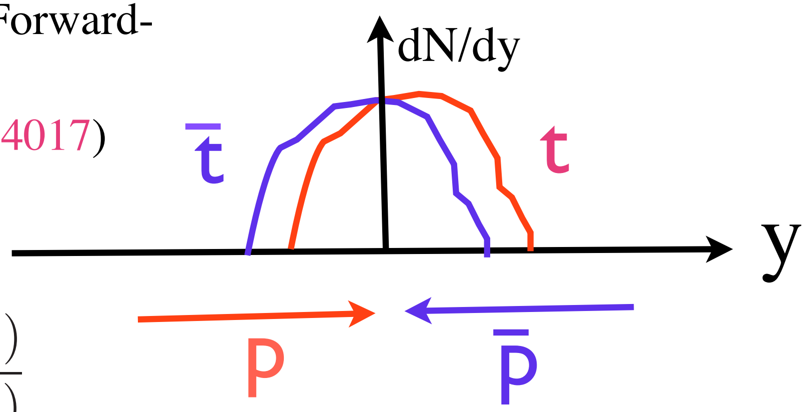
Measured inclusive b-bbar and c-cbar cross sections in $\eta \in (2.5 - 4.0)$ and $p_T > 5$ GeV/c.

Future: use larger statistics. Analysis at 8 TeV. Study b-bbar correlations.

The central-forward $b\bar{b}$ asymmetry A_{FC}

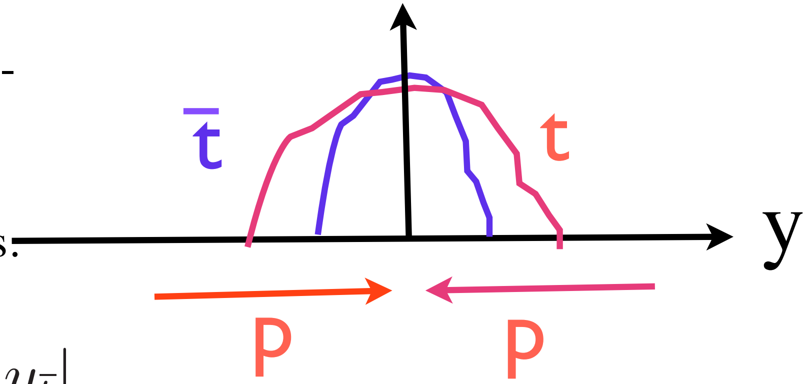
LHCb-CONF-2013-001

TEVATRON has proton-antiproton collisions: can measure a Forward-Backward Asymmetry A_{FB}.
SM prediction for t-tbar is A_{FB} ~5% (Phys. Rev. D59 (1999) 054017)
CDF and D0 observe a value ~3 to 4 times larger.
=> The discrepancy is ~2.5 sigmas.



$$A_{t\bar{t}} = \frac{N(y_t > y_{\bar{t}}) - N(y_{\bar{t}} > y_t)}{N(y_t > y_{\bar{t}}) + N(y_{\bar{t}} > y_t)}$$

LHC has proton-proton collision: can only measure the Forward-Central Asymmetry A_{FC} which is predicted to be ~1% in the SM (JHEP 01 (2012) 063): top quarks with larger rapidities are preferred, anti-top produced more frequently at smaller rapidities.



$$A_{FC} = \frac{N(\Delta_y > 0) - N(\Delta_y < 0)}{N(\Delta_y > 0) + N(\Delta_y < 0)} \qquad \Delta_y = |y_t| - |y_{\bar{t}}|$$

=> Present results at LHC are consistent with SM.

Relation between A_{FB} and A_{FC} see: arXiv:1105.4606 (from New Physics A_{FC} ~1/5 - 1/10 of A_{FB})

A_{FC} in $b\bar{b}$

Measurement of asymmetry for b-quarks can provide additional information
[Kahawala, Krohn, Strassler, arXiv:1108.3301]

Measurement dominated by contribution from $gg \rightarrow bb$.
Increase sensitivity to SM/non-SM by taking forward events and $m_{bb} > 100$ GeV/c^2
i.e. enrich events with $qq \rightarrow bb$, and $qg \rightarrow bbg$

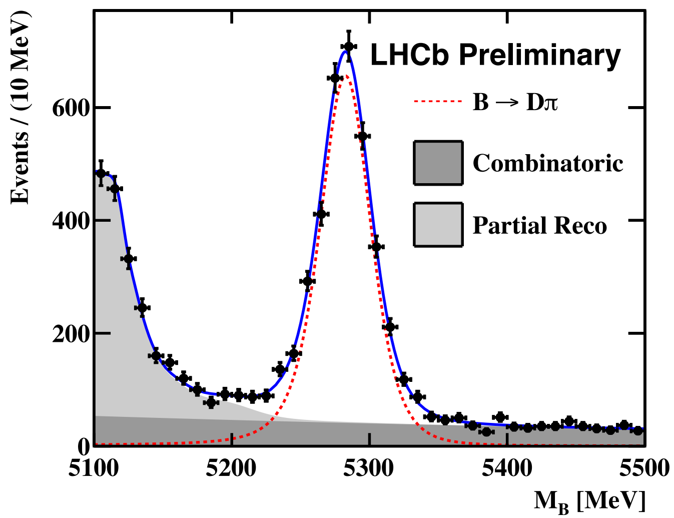
Analysis of 1.0 fb^{-1} of data at 7 TeV.

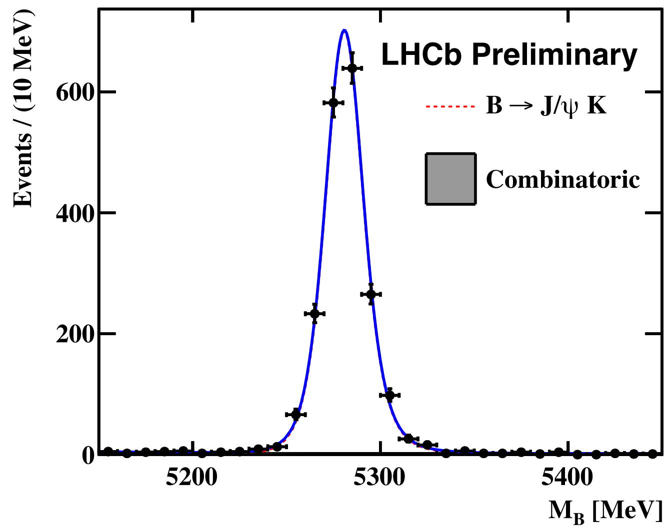
* Two jets from anti-k_T (R = 0.5), $p_T > 15$ GeV/c, $\Delta\phi(j_1,j_2) > 2.5$ rad, $2<\eta<5$, and correct jet energy to quark level.
* b tag based on vertices formed by 2, 3 or 4 tracks significantly displaced from the primary vertex => very high purity from a BDT. Charm contamination negligible.
* Flavor tag: hardest displaced track ($p>10$ GeV/c, $\chi_{IP}^2 > 16$) must be a muon.

- Resolution on $\Delta y \sim 0.1$ => no significant dilution on A_{FC}.
- $\sigma(m_{bb}) \sim$ 15-20 %, no unfolding procedure for the moment. Effects on $A_{FC} \sim 1\%$.
- Dilution of flavor tag from B^0 and B_s^0 oscillations, decays via a c-quark, muon mis-ID.

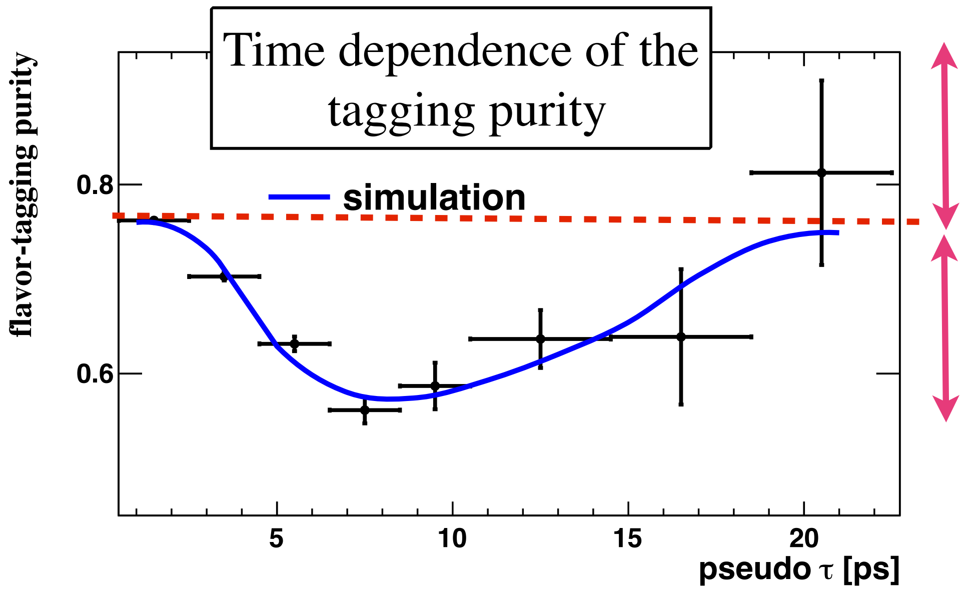
Purity values computed from MC, from data with fully reconstructed B^+, and from double tag events coincide.

A_{FC} in $b\bar{b}$





B candidate masses for $B^{\pm} \to D^0\pi^{\pm}$ and $B^{\pm} \to J/\psi\, K^{\pm}$ used in the flavor-tag studies.

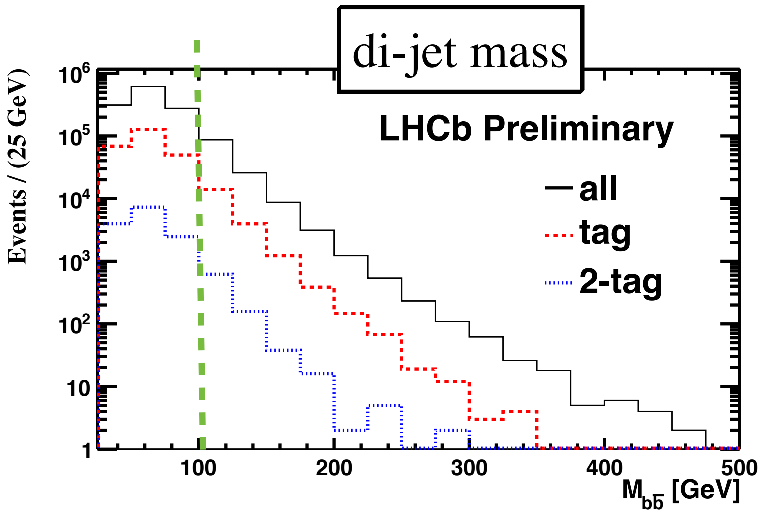


~20% mainly from $b \to cX, c \to \mu\nu X$

time integrated ~10% from B^0 oscillations

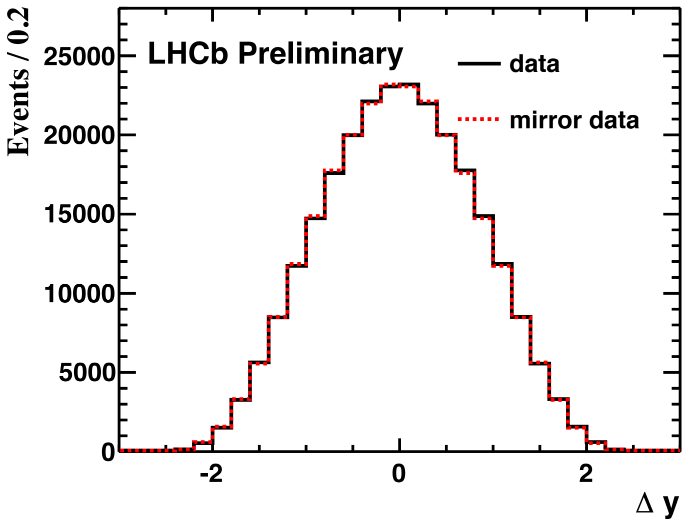
time integrated total tagging purity (70.7±0.4)%

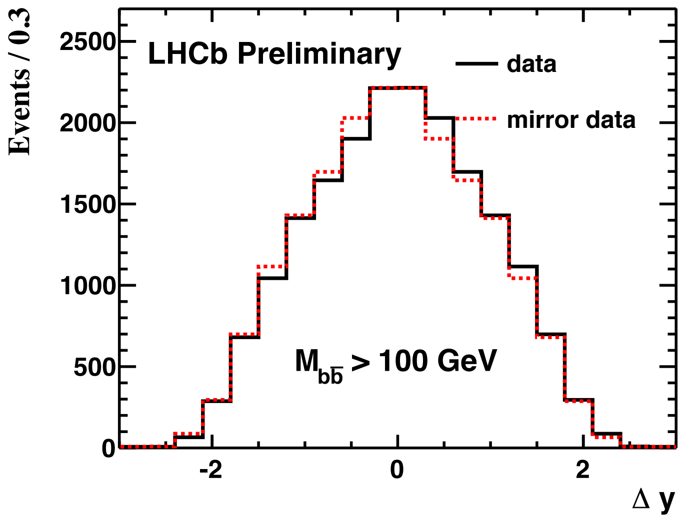
A_{FC} in $b\bar{b}$



Single tag sample : 2.6×10^5 events
Double tag: 1.5×10^4

Full statistics is used in the final analysis.
Double tag for control.





Observed $\Delta y = |y_b| - |y_{\bar{b}}|$ distributions for all events and for $m_{bb} > 100$ GeV/c^2. Reflected plots along $\Delta y=0$ in red.

A_{FC} in $b\bar{b}$

After correction for mis-tag, we obtain:

$$A_{\rm FC}^{b\bar{b}} = (0.5 \pm 0.5\ ({\rm stat}) \pm 0.5\ ({\rm syst}))\%,$$
$$A_{\rm FC}^{b\bar{b}}(M_{b\bar{b}} > 100\ {\rm GeV}) = (4.3 \pm 1.7\ ({\rm stat}) \pm 2.4\ ({\rm syst}))\%.$$

where:

$$A_{FC}^{b\bar{b}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)} \qquad \Delta y = |y_b| - |y_{\bar{b}}|$$

Systematic errors from flavor-tagging purity and detector asymmetry (seen in events tagged μ^+ vs μ^-, but ~cancellation when two sub-samples added).

Conclusion:
A_{FC} measured in the system $b\bar{b}$.
Several improvement on the analysis are under study, in particular a more efficient b-tag, and m_{bb} resolution unfolding. Adding 2012.
=> Should increase the m_{bb} > 100 GeV/c^2 mass sample by a factor of 6. We also have good hope to present results beyond the t-tbar threshold.

h^0 to Long-Lived Particles

1) Minimal Supersymmetric SM with R-Parity and Baryon number violations

L. M. Carpenter, D. E. Kaplan, and E.-J. Rhee,
"Six-Quark Decays of the Higgs Boson in Supersymmetry with R-Parity Violation", Phys. Rev. Lett. 99 (2007) 211801

$$h^0 \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 \qquad \tilde{\chi}_1^0 \to 3\,\text{jets}$$ (~70% cases with a b)

2) Hidden Valley

M. J. Strassler and K. M. Zurek,
"Echoes of a hidden valley at hadron colliders" , Phys. Lett. B651 (2007) 374

$$h^0 \to \pi_V^0 \pi_V^0 \to b\bar{b}b\bar{b}$$

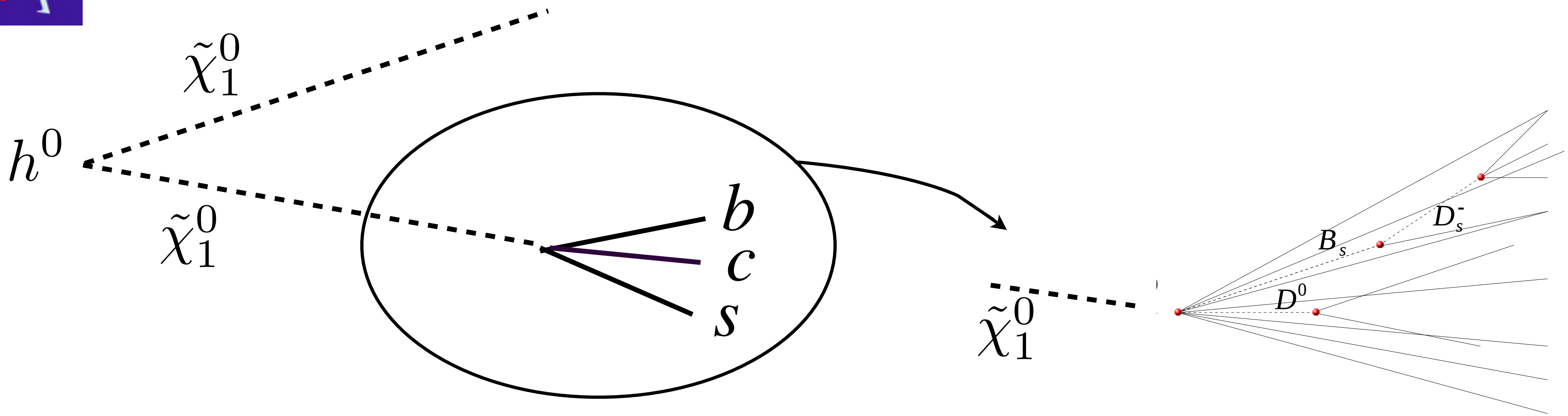
Both: $m_{LLP} > 20\,GeV/c^2 \qquad \tau_{LLP} > 1\,ps$

=> find two massive Long-Lived Particles (**LLP**) in the event
=> combine to form h^0

Models shown in the plots

Model	τ_{LLP} ps	m_{LLP} GeV/c^2	m_{h^0} GeV/c^2	
BV48	10	48	114	RPV, B violation
HV10	10	35	120	Hidden Valley

H→LLPs

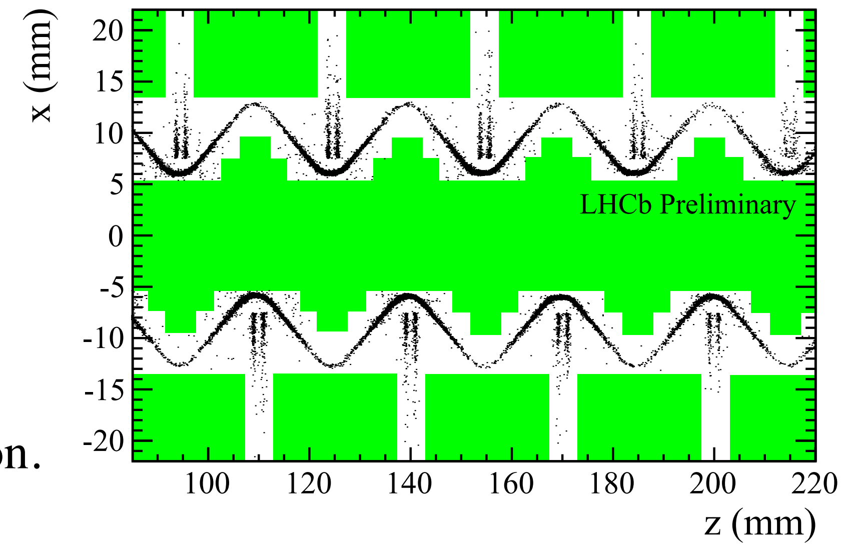


* At least one PV with ≥ 10 tracks (≥ 1 backward, ≥ 1 forward), radial distance to the beam line r < 0.3 mm

Loose selection:

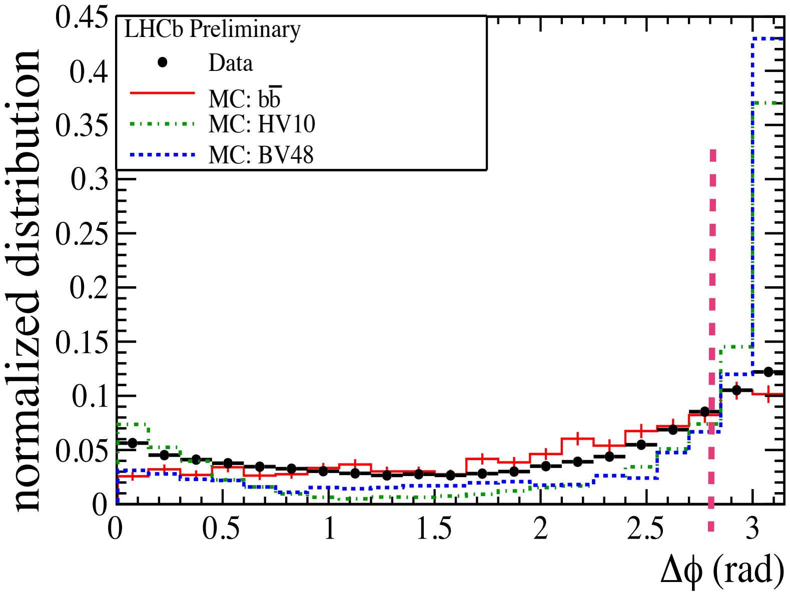
* At least two LLP candidates with
  - nb of tracks ≥ 4
  - mass > 3 GeV/c^2
  - radial distance from beam line > 0.4 mm

Main background at this point: interactions with matter, mainly Si sensors, and the RF screen.
We select only LLP candidates with vertex in the green region.



H→LLPs

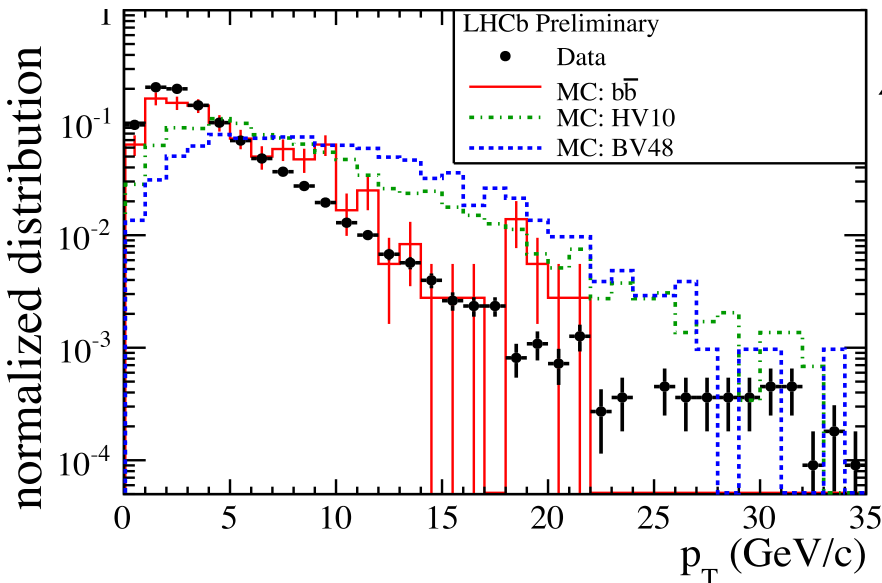
Data (35.8 pb^{-1}) compared to MC: $b\bar{b}$, HV10 and BV48

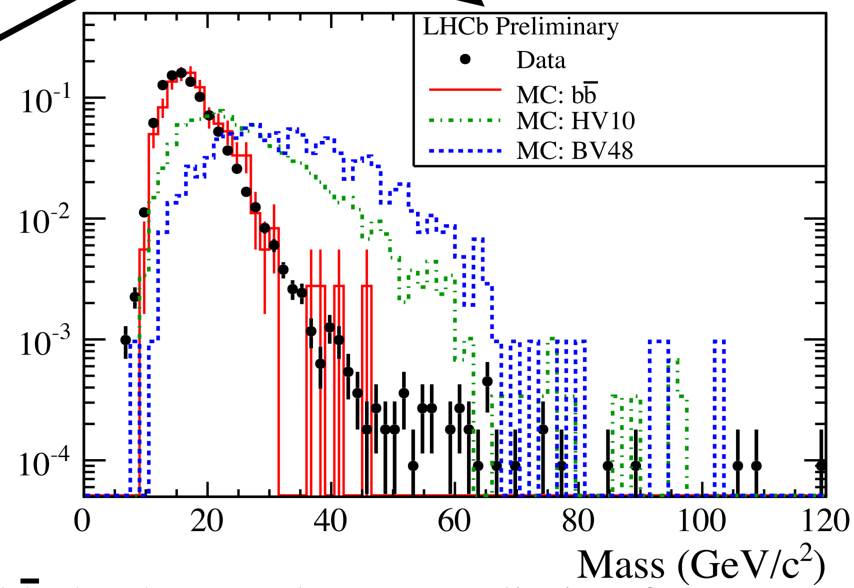


MC predicts LLP candidates are back-to-back: Δϕ is the azimuthal angle they form with the PV. Cut:

$$\Delta\phi > 2.8$$

Then combine two LLPs to form the Higgs





59k events selected, compatible with $b\bar{b}$ background (MC prediction for pure $b\bar{b}$ is (75 ± 13)k events, assuming σ_{bb} = (287 ± 40) μb)

$H \to$ LLPs

FINAL selection to reject all b-bbar events (t-tbar, minbias, idem):

* The two LLP candidates must have
  nb of tracks ≥ 6 mass > 6 GeV/c^2 vtx position errors $\sigma_r < 0.05$ mm, $\sigma_z < 0.24$ mm

=> **No data events survives the final selection**.

MC is used to obtain the selection efficiency. For BV48 we obtain a value of 0.38 %.
=> BR × sigma upper limit = 32 pb (95% CL)

Several points of the 3D parameter space studied with full simulation. A fast simulation is then used to cover a larger region of the parameter space. Two examples (units is [pb]):

LLP lifetime = 10 ps

m_{LLP}	30	35	40	48	55
m_{h^0}					
100	101	58	44	58	
105	100	75	44	39	
110	132	75	56	34	
114	128	91	47	32	46
120	148	93	58	34	31
125	179	90	61	41	29

Higgs mass = 114 GeV/c^2

m_{LLP}	30	35	40	48	55
τ_{LLP}					
3	210	156	136	168	410
5	145	101	68	58	137
10	129	91	47	32	46
15	155	90	49	31	33
20	131	93	63	32	31
25	142	100	61	34	25

Conclusion:
Preliminary analysis with 36 pb^{-1} sets limits on $h^0 \to \tilde{\chi}_1^0 \tilde{\chi}_1^0$
Analysis of 2011 data and 2012 should increase sensitivity by a factor of ~10.
Searches will be extended to other topologies, including single LLP.

Global conclusion

- LHCb can explore kinematical regions complementary to ATLAS and CMS
- Tools have been developed for reconstruction of jets and b tagging them with good efficiency&purity
- Measured
  - b-bbar and c-cbar inclusive cross section
  - A_{FC} for b-bbar
- Set limits on neutral Higgs production in the forward direction
- Higgs in associated production analysis ongoing

* 13-14 TeV operation will improve the acceptance to decay products from heavy resonances
* Upgrade very welcome